WARGAMING ULTRA-FAST PROPAGATION ALGORITHMS FOR FASTPROP

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1. OVERVIEW

The purpose of this paper is to describe a set of algorithms that provide ultra-fast simulation of propagation through the atmosphere. First, the requirement is established for this type of simulation as opposed to other valid types of simulation. Next, the reason for a new set of simulation algorithms is shown by pointing out the limitations of other methods. The main part of the paper describes the algorithms.

2. THE S1M[JLATION REQUIREMENT

The word "simulation" can apply to a variety of activities -- numerical solution of fluid flow, message traffic, pilot training in a flight simulator, and many more. An explicit meaning for "simulation" must be assigned or else there can be considerable confusion.

The purpose of a weather simulation in wargaming is to quantify the impact of weather on system performance. Once quantified, steps can be taken to optimize, procure, or reject the system. There are at least three categories of weather impact quantification:

2.1 **System Physics aud Engineering.** The goal is to determine system limits, i.e. under what conditions wil I the system work.

2.2 **System Effectiveness. How** efficient is the system when deployed? This question is asked for a variety of situations from the simple one-on-one case up through theater level conflict. An important tenet sometimes overlooked is that extreme weather can defeat any system. The question is **WHERE** and HOW OFTEN? Another tenet often overlooked is that an offensive weapon can usually wait for good weather; the effectiveness of a defensive weapon is measured in all weather.

2.3 **Training.** Two different goals differentiate the role of weather in training.

2.3.1 In a **Specified Syllabus, specific** weather is needed that develops the desired skill. The weather need not even be realistic - having five adjacent jet streams would quickly hone a pilots skill.

2.3.2 In a **Learning Exercise,** besides learning skills, lessons are learned about system usage, tactics, etc. Weather must be within the specified climate or else the wrong lessons will be learned.

The methods detailed in this paper are designed to meet goals 2.2 (system effectiveness) and 2.3.2 (learning exercises). However, these methods can be employed effectively for specified weather.

Of all weather impacts, seeability (both passive and active -- visual, IR, radar) is needed at the most frequent intervals, requires the most calculations, arid varies most rapidly. Although there is more to seeability than j ust transmission, rapid calculation of propagation through the atmosphere is the vital first step. Propagation also affects radio and optical communications. Thus, the rest of this paper focuses on propagation.

Numerous calculations of propagation are generally required. The large number is due to the number of sensors and targets, and the fact that they can rapidly change location. For many applications, a complete scene must be rendered and displayed. In addition, many simulations require multiple views – as seen by a land observer, a pilot, a radar, an infrared sensor, etc. FASTPROP generates a virtual atmosphere scenario and then allows ultra-fast calculations within it.

3. THE DILEMMA

Facts and premises are only stated here. Justification is found in Boehm (1994c), Boehm (1995), Boehm (1996), and LaMar et al. (1994).

The atmosphere has layers that are effectively uniform with respect to transmission, but there are other layers, particularly those with clouds, that have intricate detail. It is the intricate detail that is hardest to specify and often has the strongest effect on propagation.

Current physical fluid dynamic methods cannot specify intricate details in the atmosphere. The basic problem is not the lack of computer power nor observations of initial or boundary conditions. It is due to lack of complete physical principles with respect to the stress tensor, water dropl et/crystal/vapor transformation, and radiation flux in clouds. For example, the size of cloud puffs within a cloud can not be found using only first principle physics. That is not to say that such relationships will never be discovered, and work in such area should be encouraged. But the fact remains that there are unknown areas in the basic equations for turbulent motion and “ in water transformations in the atmosphere.

Clouds and associated rain contribute the most to the variability of propagation, yet are poorly measured. Standard surface observations give only fractional cover and type -- no information is recorded on orientation, shape of gaps, or physical properties. Cloud types are based on visual appearance. The liquid water per cubic meter can vary over an order of magnitude within the same cloud type. Weather satellite data must use inferential methods of limited accuracy to determine cloud properties. Current archived observations fall far short of specifying intricate detail in the atmosphere. Only a small fraction of atmospheric motion and constituents are actually measured.

Furthermore, raw observations contain a host of biases, idiosyncrasies, and instrument and archiving errors to fool the unwary simulator.

Current methods of calculating propagation are much too slow for operational simulation. MODTRAN running on a high end work station would take several days to calculate the radiances in a single picture.

A propagation beam is affected by structure of many scales -- from a single droplet on a sensor lens to a complete cloud field when viewed from hundreds of kilometers away as shown in Figure 1.

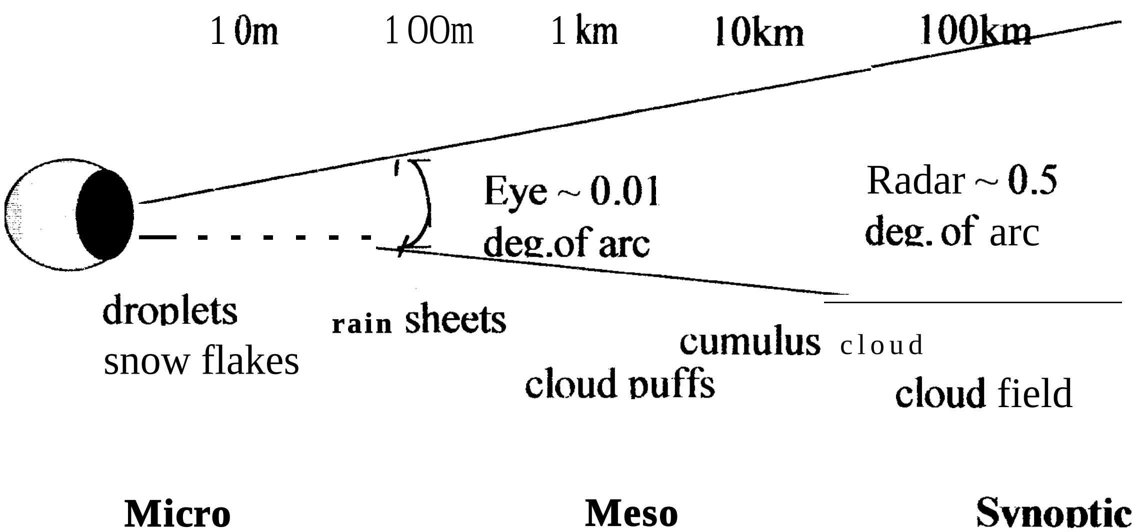

FIGURE 1. The scale of objects seen in a beam is a function of distance

Meteorologists have for many years divided atmospheric motion into various scales depending on what forces are important at that scale. Various scales, from a single droplet (e.g. on a lens) to large domains as seen by a distant millimeter system, are required for effective propagation simulations.

Propagation is along a beam which is not infinitesimally thin, but can often be described by a cone specified by some solid angle. The width of this cone at the target or at some atmospheric obstruction can be measured as the distance across the beam. There are beams which are very narrow (a centimeter or less in width), very short (less than 50 meters), very wide (1 O km or more'), or very long (500 km or more). What a sensor sees when looking through the atmosphere depends very much on its beam width and path length.

A meteorological satellite infrared sensor may have a beam width of 3 km or more at the height of the clouds. A high resolution surface based infrared sensor may have a beam width of less than 5 meters when looking at the same cloud. What they see will not have the same emissivity nor structure. A realistic simulation must have the abi lity to provide propagation at various scales.

There are numerous statistical and stochastic models of the atmosphere that have been validated for specific purposes. These range from simple rain/no rain Markov chains to complex four-dimensional non-homogeneous anisotropic global models such as CFARC which produce minute be minute results for decades. However, a new kind of stochastic algorithm was needed to meet the ultra fast computation requirements.

4. Algorithm Design

In order to overcome the limitations of other methods, three methodologies were developed: 1. The Morficon, 2. Stochastic Indexing, and 3. HEFeS (Hierarchical Environmental Feature Structure). Together the three methods can form a weather expander. This weather expander takes a small set of input values and using stochastic generators produces a complete weather scenario.

4.1. The Morficon

Consider the calculation of monochromatic transmission along a beam,

$$I_S = I_T e^{\int_S^T Kdx} \qquad (1)$$

Where I_S is Illumination at sensor S

I_T is Illumination at target T

K is the absorption coefficient

x is along a line-of-sight

[f the line-of-sight is through a homogeneous layer, then the calculation is straight forward. Many transmission codes do just that; they assume a series of homogeneous layers.

In a region of intricate detail, a more general method is needed. A series of grid points along the line-of-sight can be defined and absorption interpolated to these points. However, a regularly spaced grid is inefficient. There are too many grid points where there is little change and too few where there is intricate detail.

The Morficon algorithm overcomes this shortcoming and has other desirable attributes as well. Instead of using ray tracing methods to render a scene, radiometric properties are precalculated for each object under various lighting conditions and stored as prototype objects called morficons. These morficons are stretched (morphed is the computer term) to adjust for viewing perspective, exact lighting, and individual shapes. By selecting a set of morficons based on physical and climatological principals, the resulting scene is consistent with the climatology of the place and time and the physics of the atmosphere. For homogeneous or linear gradient objects, the transmission can rapidly be calculated using sumations over objects,

$$I_S = I_T e^{\sum_{i=1}^{n} K_i \Delta x_i} \quad or \quad \ln(I_S) = \ln(I_T) + \sum_{i=1}^{n} K_i \, \Delta x_i \tag{2}$$

where K_i is the absorption coefficient for the ith object or K_i is $(K_{enter} + K_{exit})/2$ for a linear gradient object. Subscripts enter and exit indicate where the line-of-sight enters and exits the 'object. Axis the distance along the line-of-sight through the object.

The morficon is not merely a computer trick to produce fast images, although it does appear to be one of the fastest ways to generate an image. Propagation calculations generally require various parameters to be integrated along a line of sight. Typically. a grid of these parameters is used to interpolate the parameters to spacing along the line of sight. These values are then summed to approximate the integration.

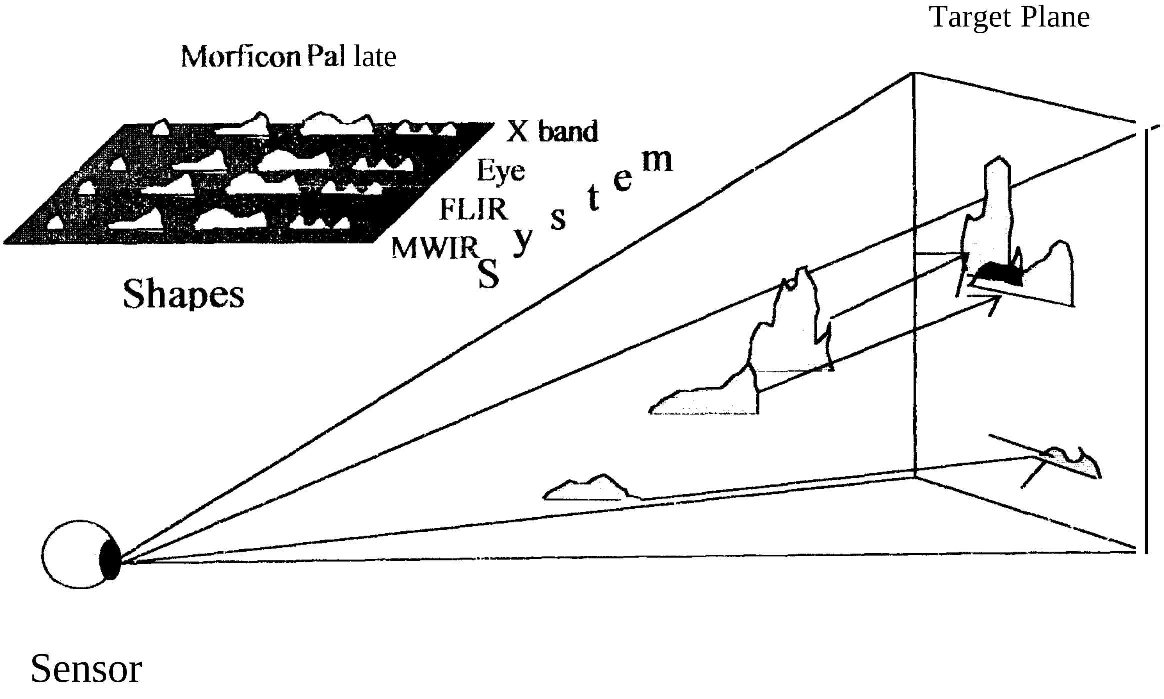

FIGURE 2 The transmission of various object is rapidly projected onto a plane at the distance of the target. Values on this plane can be added to objects beyond the target plane to produce a background plane.

With a morficon, the exact value of the distance through an object (e.g. a cloud) is known. Also the exact value of transmission or other parameter is know. These values are summed up by adding morficons to a target plane. The results are exact line-of-sight integrations – to within computer precision. See Figure 2.

A pallet of morficons is used to provide calculations for various sensors and atmospheric structures. Usually there is a tradeoff between speed and accuracy. With the morficon, both ultra-speed and accuracy result. Part of this advantageous situation is due to the prior calculation in making the morficon palette.

4.2 STOCHASTIC INDEXING

Rather than store all the information for viewing from different angles, the reproducibility property of pseudo-random number generators is used to index location and properties of each object. This "Stochastic Indexing" allows for millions of objects to be specified and retrieved with nearly zero storage. A backward running random number generator allows desired properties (e.g. 95% coldest temperature) to be generated. Algorithms are described and computer routines are presented in Boehm and Willand (1996). An illustrative demonstration of stochastic indexing is found in Boehm (1994b).

The typical computer random number generator starts with a seed number and rapidly returns one or more numbers -- a sequence -- that appears to be random. However, if the same starting seed is used, the exact same sequence will result.

Many types of scene-generating algorithms use this feature to produce the same scene by using the same seed. But if only a part of the scene is needed, the whole scene must be redone in order to obtain that section of the sequence pertinent to the desired part. If an inverse Fourier transform method is used, the whole random sequence must be calculated to get the random phases (the amplitudes are usually set to produce a desired spatial spectrum).

Stochastic Indexing goes one step further. it uses multiple starting seeds to generate what is needed at a point. The advantage of stochastic indexing is that the very large number of objects required for intricate detail can be indexed rapidly without a huge data base.

4.3 HEFeS (Hierarchical Environmental Feature Structure)

A hierarchy of feature objects, see Table 1, has been devised to specify structure over the scales of interest. We know from work reported in Boehm et al. (1993) and Eis (1997) that structure is not. scale invariant. That is, structures at one scale do not occure at the same frequency (or sometimes at all) at other scales. To say the same thing another way, some of the terms in the equations of motion that are dominant at one scale are negligible at other scales.

The location and orientation of sub-objects are relative to the parent object. This technique allows rapid sorting of objects as to whether they are in a view or not, since the sub-objects do not need to be checked if the parent object is out of view.

TABLE 1 Typical HEFeS Objects

OBJECT CLASS	TYPICAL SIZE	TYPICAL TIME	EXAMPLE
Climate regime	global	1 month	wet spring
planetary wave	5000km	1 week	zonal jet
synoptic feature	1 Oookm	3 days	cold front
meso feature	1 Ookm	12 hours	squall line
c1 uster	1km	1 hour	cloud cluster
cell	30m	10 min.	cloud cell
sheet	5m	5 min	rain streamer
voxel	1m	10 sec.	droplet dist.
particle	1mm	1 sec	snow flake

4.4 Climatology to Simulation Parameters – PARGET

The purpose of PARGET, 'Parameter GETer", is to specify the parameters of the simulated atmosphere so that ii is representative of a given location, season, time of day and/or desired weather. PARGET transforms general user specifications into parameters required to establish a specific HEFeS Specification. PARGET consists of five sections: 1. Input Interface ,2. Output Interface, 3. Logic Section, 4. Stochastic selection, and 5. HEFeS Climate Data. Only a portion of PARGET wi ll be discussed here, namely the types of input and an i Illustrative example of stochastic selection from a climatic distribution.

4.4.1 The input to PARGET is location, time of day, time of year, and kind of selection. The kind of selection is ***one*** of three:

4.4.1.1 A random draw from the appropriate climate.

4.4. "1.2 A selection of a percentage and a condition for the percent worst observed condition. The condition may be a single variable, rain rate, or it may be a joint condition such as the lowest ceiling and/or visibility.

4.4.1.3 A specified feature. The feature may be a desired condition such as a large thunderstorm right there. The feature may also be a point observation or forecast, - e.g. a METAR surface observation or TAF. The specified feature may be at any scale. For example, the feature may also be a synoptic field. (See Boehm, 1995) or it could be a droplet on a sensor's lens. in either ease, the other scales of objects are selected to be consistent with the specified feature.

4.4.2 An illustrative example of stochastic selection is the rain rate for Northern Israel. Based on the algorithms developed by Tattleman et al. (1995), it was found that the climatic probability of rain rate for the month of February is,

$$p = \Phi[3.5 + 0.955 \, Ln(R)] \quad (3)$$

where P is the probability, R is the rain rate in mm/min, and@ is the cumulative normal function.

Equation 3 is easily inverted to find the rain rate that corresponds to a specified probability,

$$R = \exp[\Phi^{-1}(P) - 3.5/ 0.955] \quad (4)$$

where Φ^{-1} is the i nverse cumulative normal distribution.

Thus, if the percent heaviest, P, is specified, the corresponding rain rate, R, for northern Israel in February can be calculated for use in simulating the 100 P percent heaviest precipitation Following Tattleman (1994) the Liquid Water Content, LWC, can also be calculated,

$$LWC = 0.052 \, R^{0.864} \quad (5)$$

5. Recapitulation

The HEFeS/Stochastic Indexing/Morficon combination is an accurate, very fast method for simulation of weather impacts in a relatively small inexpensive program. Some desirable capabilities such as the 95% worst si m u] ation are hard to do any other way.

Many people have trouble grasping the stochastic generator concepts. They appear too simple. However. the underlying laws are quite complex indeed. To some they appear as Voodoo. However, stochastic laws rest on theorems and proofs much tighter than most meteorological derivations.

6. ACKNOWLEDGMENTS

This work was supported by the Geophysics directorate of the Phillips Laboratory with Mr. Donald D. Grantham as contract monitor for contract number F19628-93-C-0051 and by the US Army Space and Strategic Defense Command with Chuck LaMar as project leader.

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